

PROCEDURES AND DESIGNS USEFUL FOR SCREENING MATERIAL IN  
SELECTION WORK WITH PARTICULAR REFERENCE TO PLANTS<sup>1</sup>

BU-131-M

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March, 1961

ABSTRACT

The paper represents a brief review of results on screening. The references listed in the paper were selected to illustrate diversity of topics related to screening procedures with particular attention being paid to the results for plant and animal breeding screening programs. Also, the large number of journals involved should be noted. In this form, it is hoped that researchers involved in screening various drugs, pesticides, fumigants, herbicides, etc. will become acquainted with the topics and some of the literature on screening in breeding fields, and vice versa. With this in mind, the similarities in a biochemical and in a breeding program were stressed. In particular, the developmental phase, the evaluation phase, and the production or maintenance phase are common to both fields. Many of the statistical results obtained in one field are applicable to the other.

No discussion is given concerning unsolved statistical problems related to screening. This subject is discussed in papers by Armitage and Schneiderman, Cochran, Davies, Dunnett, Finney and Yates. Some comments are given on experimental designs useful for screening experiments. Particular reference is made to the class of designs known as augmented designs.

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<sup>1</sup> This work has been supported in part by NIH Grant RG5900, Biometrics Unit, Cornell University, and was presented as a lecture at the National Institutes of Health, Bethesda, on 3/15/61.

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I. INTRODUCTION

The aims of this paper are to point out some similarities of plant breeding research and biochemical research on new materials (drugs, pesticides, herbicides, fumigants, etc.), to outline a screening program in plant breeding, to present some experimental designs useful in screening experiments, and to present a partial bibliography on screening procedures.

Although Davies [1958] emphasizes the differences in screening drugs and plant selections, the similarities will be stressed here. The screening procedure for plant breeding outlined below (Sections II and III) is taken from Finney's [1958b] excellent discussion of varietal selection in plant breeding programs. In addition to the above references, the reader is referred to papers by Armitage and Schneiderman [1958], Bechhofer [1954,1958], Cochran [1951], Curnow [1959,1960], and Dunnett [1960], as well as to several of the remaining references, for a comprehensive discussion of statistical problems encountered in screening material for selection of superior types. An attempt is made here merely to outline some of the results obtained.

The screening is usually for a single characteristic (say  $y$  which is measured by  $X=y+\text{error}$ ), but in many situations it may be necessary to use an index of several observed characteristics, say  $\sum_i b_i X_i = I$ , and to screen on the basis of the index [Cochran, 1951; Finney, 1956a, 1956b, 1958a, 1958b, 1960; Kempthorne, 1957; Lerner, 1950; Smith, 1938]. Many papers have been written by animal breeders [e.g., Dickerson and Hazel, 1944; Lerner, 1950; Lush, 1945] on the construction and use of indices. These, for the most part, are not included in the references at the end of this paper.

Criteria for screening work depend upon several items. Some of these are:

- i) The ratio of the selectable or treatment variance component to the error variance component.
- ii) The suitability of present standard treatments (i.e., none available, unsatisfactory standards, satisfactory standards, etc.).

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- iii) The economic or social potential of increase in the desired characteristic or characteristics.
- iv) Selection of the single best, of the best  $t$  out of  $N$ , or of the best fraction, say  $\pi$ , out of  $N$ .
- v) The number of characteristics used in screening.
- vi) The incidence of the disease or pest in the population.

Some or all of the above in addition to other items may need to be considered in a screening program on new treatments.

## II. PHASES IN A SCREENING PROGRAM

As described by Finney [1958a, 1958b] for plant breeding work, the improvement in performance of a treatment (variety, chemical, sire, etc.) from the adoption of new treatments involves three phases. These are:

- i) The development of new treatments (strains, chemicals, etc.).
- ii) The evaluation of the new treatments in comparison with standards.
- iii) The preservation, production and multiplication of superior materials for commercial usage or for further use in phase (i).

In the developmental stage in breeding studies, the greatest genetic progress is made through utilization of genetically superior populations. The breeder, plant or animal, makes full use of genetic principles in developing genetically superior populations from which to develop the new strains for evaluation. Likewise, the chemist utilizes the family of compounds mostly likely to produce superior chemicals for the phenomenon of interest. The chemist makes full use of chemical and biological theory in the development of "chemically superior" compounds. Just as lethality, sterility, etc., are problems of the breeder, toxicity, detrimental side effects, etc. are problems of the biochemist. The breeder may utilize a single mendelian character whereas the chemist may use a single atom or radical (e.g., substitution of chlorine for OH) in their respective research programs. It would appear that there could be fruitful interchange of ideas and methods between the two fields despite the fact that many differences exist [Davies, 1958].

The breeder must rely heavily on genetic and agronomic theory in the developmental phase. This does not mean, however, that there are no statistical problems associated with this phase. The efficiency of various breeding procedures (back-crossing, selfing, sibbing, etc.) and of population and generation for evaluation

[Dickerson and Hazel, 1944; Lush, 1945, 1947; Rajagopalan, 1958; Sastray, 1956; Smith, 1960; Sprague, 1946] have received only limited attention from the statistician. Some work has been done on the problem of minimum and optimum population sizes,  $N$ , of new treatments (genetic populations) [Graybill and Kneebone, 1959; Hanson, 1959; Nordskog, 1959; Osborne, 1957; Powers et al., 1958; Rendel, 1959; Robertson, 1957, 1960]. Despite the fact that there are statistical problems in the developmental stage, the primary problems are non-statistical. A comprehensive survey of all problems is essential for efficient breeding programs as well as for other research programs. A complete understanding of the developmental phase is highly conducive to rapid progress in the research program. A complete statement is useful [e.g, Mangelsdorf, 1953; Warner, 1953]. The biochemist faces many of the problems described above.

Whether or not the developmental phase and the evaluation phase can be completely separated depends to a large extent on the kind of material. Some discussion of this for plant breeding has been presented by Finney [1958b], Lupton and Whitehouse [1956] for cereals, Mangelsdorf [1953] for sugar cane, Warner [1953] for sugar cane, and by Yates [1950].

### III. STAGES IN EVALUATION

As described by Finney [1958b], the selection program for a given batch of material may be considered to consist of  $k$  stages. At each stage a proportion  $P_i$  of the remaining treatments will be retained and a proportion  $1-P_i$  will be discarded. In tabular form, the selection program is of the form:

Stage	Proportion selected	Number selected	Size of population at stage $i$
1	$P_1$	$P_1 N$	$N$
2	$P_2$	$P_2 (P_1 N)$	$P_1 N$
3	$P_3$	$P_3 (P_1 P_2 N)$	$P_1 P_2 N$
$\vdots$			
$i$	$P_i$	$P_i \left( \sum_{j=1}^{i-1} P_j \right) N$	$\left( \sum_{j=1}^{i-1} P_j \right) N$
$\vdots$			
$k$	$P_k$	$P_k \left( \sum_{j=1}^{k-1} P_j \right) N$	$\left( \sum_{j=1}^{k-1} P_j \right) N$

where  $\pi = P_1 P_2 P_3 \dots P_k$  = fraction of  $N$  treatments selected at the end of the selection program.

The particular population started at time  $j$  will be denoted as the  $j$ th cohort. In many programs there may be  $k$  or more cohorts under test at any one time. Thus, one cohort might be in stage  $k$ , a second cohort in stage  $k-1$ , a third cohort in stage  $k-2$ , ..., a  $k$ -1st cohort in stage 2, and a  $k$ th cohort in stage 1. If a cohort is completely discarded at stage  $i$ , then the selection fraction  $P_i$ , and consequently  $\pi$ , is zero.

If the initial population  $N$  is too large to handle in stage 1, an initial random discard is made and the number of entries retained for stage 1 is  $P_0 N = N'$ , and  $N'$  replaces  $N$  above. This initial random discard may appear strange, but if nothing is known about the  $N$  treatments (strains or chemicals), there is no reason for using a non-random sample. The  $(1-P_0)N$  entries may be saved for stage 1 of the next cohort, or the  $(1-P_0)N$  entries may never be tested because of the poor showing of the  $P_0 N$  entries. This would mean that the effort of producing the  $(1-P_0)N$  entries was wasted and could be charged off to poor coordination in the developmental and evaluation phases.

In other situations, a fixed number, rather than a fixed percentage is saved at each stage. At the end of the  $k$ th stage the researcher would end up with  $t$  entries, say, regardless of the value of  $N$ . Even in this situation,  $\pi$  can be selected so this is approximately achieved and hence, the literature on the selection of a specified fraction,  $\pi$ , can be utilized to obtain an approximate solution to the problem of selecting a fixed number of treatments.

#### IV. THE PRESERVATION, MULTIPLICATION, AND PRODUCTION PHASE

Although there are many problems in this phase, mention of only some of the statistical problems will be made. The statistical problem of setting standards for a new variety, drug, vaccine, pesticide, etc. may be trivial in some cases and complex in others.<sup>1</sup> The control of quality and the selecting of tolerance limits of purity, are problems of commercial production of varieties, strains, and chemicals. The preservation of basic parental material is necessary in order to reproduce a variety or strain over time. Thus, results from "acceptance sampling" and "quality control" will be useful in the commercial production of new treatments.

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<sup>1</sup> In this connection it should be noted that Drs. J. A. Baker and D. S. Robson, Cornell University, are working in this area with animal vaccines.

## V. SINGLE STAGE SELECTION PROCEDURES

Many statistical procedures have been devised for single stage selection; several criteria have been used. The selection of the best treatment out of  $N$  treatments may be framed as:

- i) The determination of sample size to given a specified error of incorrectly selecting the largest population [Bechhofer, 1954, 1958; Bross, 1950; Dunnett, 1960; Grundy et al. 1956; Maruice, 1958a; Shirafugi, 1956; Somerville, 1954; Zinger and St.Pierre, 1958].
- ii) The maximization of the mean value of the characteristic ( $y$ ) while retaining a specified fraction ( $\pi$ ) of the original population ( $N$ ) [Cochran, 1951; Curnow, 1959, 1960; Finney, 1956b, 1958a, 1958b; Perotti, 1943].
- iii) The maximization of the fraction ( $\pi$ ) of the original population ( $N$ ) retained subject to the condition that the mean value of the characteristic ( $y$ ) in the universe has some preassigned value [Birnbaum and Chapman, 1950].
- iv) The maximization of the average mean value of the characteristic for the selected individuals by varying size of population of treatments ( $N$ ) and the number of repetitions ( $r$ ) on individual treatments given that the total number of observations  $rN$  is fixed [Duangratana, 1957; Federer, 1951, 1956b; Federer and Sprague, 1947; Henderson, 1954, 1956; Lowe, 1952; Sprague and Federer, 1951; Rojas and Sprague, 1952; White, 1958; Yates, 1940].
- v) The assignment of a low probability of rejection to true treatment yields which are in the upper part of the distribution ("good treatments") and a high probability of rejection to true treatment yields in the lower part of distribution ("bad treatments") [Keuls and Sieben, 1955; Sieben, 1954; Tang, 1938].

No doubt other criteria have been and will be useful for the various problems arising in either a single stage selection program or a multistage one. For example, economic and social considerations may be involved. Some research has been done on the economic aspects in connection with some of the criteria used above [Bross, 1950; Dunnett, 1960; Finney, 1960; Grundy et al. 1954; Shirafugi, 1956; Somerville, 1954; Sprague and Federer, 1951; Yates, 1952].

## VI. MULTISTAGE SELECTION PROCEDURES

As with any phase of statistics consideration of developments in other areas can be quite profitable. Therefore, in multistage selection programs, consideration must be given to sequential sampling developments and to such topics as the theory of tournaments where selection is by means of elimination en route to the selection of a winner [e.g., Bose, 1956; Bradley and Terry, 1952; David, 1959; Glenn, 1960; Kendall, 1955; Maurice 1958b; see Discussion to Dunnett, 1960, for additional references]. In addition to the above, there is a literature on selection procedures similar to the one outlined in Section III [Armitage and Schneiderman, 1958; Cochran, 1951; Curnow, 1959, 1960; Davies, 1958; Finney, 1956b, 1958a, 1958b; see Discussion to Dunnett, 1960, for additional references].

Cochran [1951, table II and section 7] presented a comparison among various selection fractions for a two-stage selection procedure. Since the comparisons are interesting his results are given below [also, see Finney, 1958b, for additional results and comments]:

Gain in  $y$  (true yielding ability of a treatment) for  
Various Methods of Two Stage Selection

$P_1$	$P_2$	$\sigma_e^2/\sigma_g^2=1$ $\rho_1=.707$	$\sigma_e^2/\sigma_g^2=3$ $\rho_1=.5$	$\sigma_e^2/\sigma_g^2=15$ $\rho_1=.25$	$\sigma_e^2/\sigma_g^2=63$ $\rho_1=.125$
1	1/24	1.745	1.352	0.733	0.375
1/2	1/12	1.867	1.507	0.858	0.452
1/3	1/8	1.902	1.592	0.948	0.501
1/4	1/6	1.936	1.637	0.996	0.532
1/6	1/4	1.947	1.649	1.035	0.564
1/8	1/3	1.935	1.630	1.032	0.572
1/12	1/2	1.867	1.529	0.970	0.547
1/24	1	1.511	1.069	0.534	0.267

where  $P_1 P_2 = \pi = 1/24$ ;  $P_1$  and  $P_2$  equals selection fraction in first and second stages, respectively;  $\sigma_e^2$  = error variance for treatment means in stage 1;  $\sigma_y^2$  = variance component due to treatments (the selectable genetic or treatment variance);  $\rho_1 = 1/\sqrt{1+\sigma_e^2/\sigma_g^2} = \sigma_g/\sqrt{\sigma_g^2+\sigma_e^2}$  [see Yates, 1940; Federer, 1951].

In the above table the gain in  $y$  for all selections at the end of the first stage (i.e.,  $P_1=\pi=1/24$ ,  $P_2=1$ ) is given in the last line of the table. On the other hand, if all selection is based on results from all entries in two stages (i.e.,  $P_1=1$ ,  $P_2=\pi$ ) the gain in  $y$  is given by the first line in the table. The former procedure results in the smallest gain regardless of the size of the ratio  $\sigma_e^2/\sigma_g^2$ . Likewise, the maximum gain in  $y$  (underlined values) is achieved for most values of  $\rho_1$  simply by using  $\sqrt{\pi}=p_1=p_2$ . In this connection and for multistage selection procedures Finney [1958b] states the following: "On the assumptions that a single yield characteristic is to be the basis of selection and that yielding capacity is normally distributed in the whole population of potential new varieties, fairly detailed results have been obtained for selection conducted in a single stage. Optimal conditions have been investigated, and rules given for obtaining the maximum improvement in yield consistent with a specified total selection intensity; this sometimes requires that a proportion of new varieties be discarded without test. For two stages, the problem is much more complicated, and little success has been achieved for any greater number. Nevertheless, there is evidence that initial discarding of varieties is now seldom advantageous and that a rule near to the optimal is: 'Allocate equal fractions of the total experimental area to each of the successive stages, and select with equal intensity at each stage, so that in  $k$ -stage selection each successive stage involves selecting a fraction that is the  $k$ th root of the overall fraction'." In addition Finney [1958b] and Yates [1950] have some interesting comments on the optimum number of stages in a selection program.

## VII. SOME ASPECTS OF EXPERIMENTAL DESIGN IN SCREENING

The experimental design for a selection program must take account of the several aspects of stratification [Finney, 1958b]. In particular, it is necessary to define explicitly the area or location of the selection program (i.e., a single location, laboratory, hospital, etc.), the time period for the program, the time of starting the program, the type of treatment involved (i.e., annual plant, perennial plant, animal with a short (e.g., drosophila, mice, poultry, etc.) or long (e.g., cattle, elephants, etc.) reproductive period, etc.), and the characteristic ( $y$ ) or characteristics involved in the selection program. In plant selection programs, for example, it is known that varieties interact with sites and years; a part of the interaction is due to time of planting. By utilizing



different planting dates for the individual replicates at one location, it is possible to improve the efficiency of the selection program considerably over that for one date of planting at one site and in one year. The efficiency of using replications over years and locations for one population of size  $N$  relative to using different populations each of size  $N$  at several locations has not been investigated. If effect, a plant breeder usually starts a cohort each year and is, therefore, using different populations of size  $N$  each year. Some breeding programs (and also some soil fumigation and insecticide programs) make a single planting of each entry at one location and use as many locations as permitted with available material.

Although the over-all experimental design for a selection program will need considerable study, some general comments can be made relative to the design of selection experiments. In most experiments checks or standards are necessary in each stage of selection and for each cohort. For the selection program defined in Section III, many of the checks could be eliminated simply by putting the  $k$  stages from  $k$  different cohorts together in one experiment. (An additional advantage accrues from comparisons among treatments from each of the  $k$  cohorts.) Different replication numbers on the entries of different cohorts may be obtained simply by using the class of designs known as augmented designs [Federer, 1956a, 1956c, 1960a, 1960b]. An augmented design is any standard one [see Federer, 1955; Kempthorne, 1952] to which additional treatments have been added. The augmented randomized complete block design with  $r$  blocks and with  $r_j$  replicates on the entries of the  $j$ th cohort [Federer, 1956a] follows:

Cohort	Stage	No. of entries	No. of entries per block <sup>1</sup>
1	$r$	$V_r$	$V_r$
2	$r-1$	$V_{r-1}$	$(r-1)V_{r-1}/r$
3	$r-2$	$V_{r-2}$	$(r-2)V_{r-2}/r$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
$r-1$	2	$V_2$	$2V_2/r$
$r$	1	$V_1$	$V_1/r$

<sup>1</sup> to greatest integer or to greatest integer plus 1

Augmented incomplete block designs and augmented designs with two- and higher-way elimination of heterogeneity for controlling experimental variation are available [Federer, 1960a, 1960b].

Yates [1936] presented a formula to determine the optimum number of checks to use in a stratum or in an experiment when comparisons of entries in different strata or experiments were to be compared through a common check (or checks). The formula is  $c = -1 + \sqrt{1+h}$  where  $c$  is the number of checks and  $h$  is the number of other entries in a stratum. The percentage of resources devoted to checks depends upon the value of  $h$ . Values of  $c$  for various values of  $h$  are given below:

$h$	$c$	$c/(h+c)$ in %	$h$	$c$	$c/(h+c)$ in %
3	1	25	3,599	59	1.6
99	9	8	4,899	69	1.4
255	15	6	8,099	89	1.1
440	20	4	9,999	99	1.0
2499	49	1.9	19,599	139	0.7

Thus, the allocation of a constant percentage of an area or of resources to checks or standards appears to be an inefficient procedure. The above results are useful in setting up augmented designs for two cohorts, say, where  $r_2$  replicates are used for each of the  $P_1N$  entries in stage 2 of one cohort and  $r_1$  replicates are used for each of the  $M$  entries in stage 1 of the second cohort.

#### VIII. DISCUSSION AND SUMMARY

The paper represents a brief review of results on screening. The references listed in the paper were selected to illustrate diversity of topics related to screening procedures with particular attention being paid to the results for plant and animal breeding screening programs. Also, the large number of journals involved should be noted. In this form, it is hoped that researchers involved in screening various drugs, pesticides, fumigants, herbicides, etc. will become acquainted with the topics and some of the literature on screening in breeding fields, and vice versa. With this in mind, the similarities in a biochemical and in a breeding program were stressed. In particular, the developmental phase, the evaluation phase, and the production or maintenance phase are common to both

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